Dark photons and other exotic searches

Martino Borsato

Universidade de Santiago de Compostela

on behalf of the LHCb collaboration

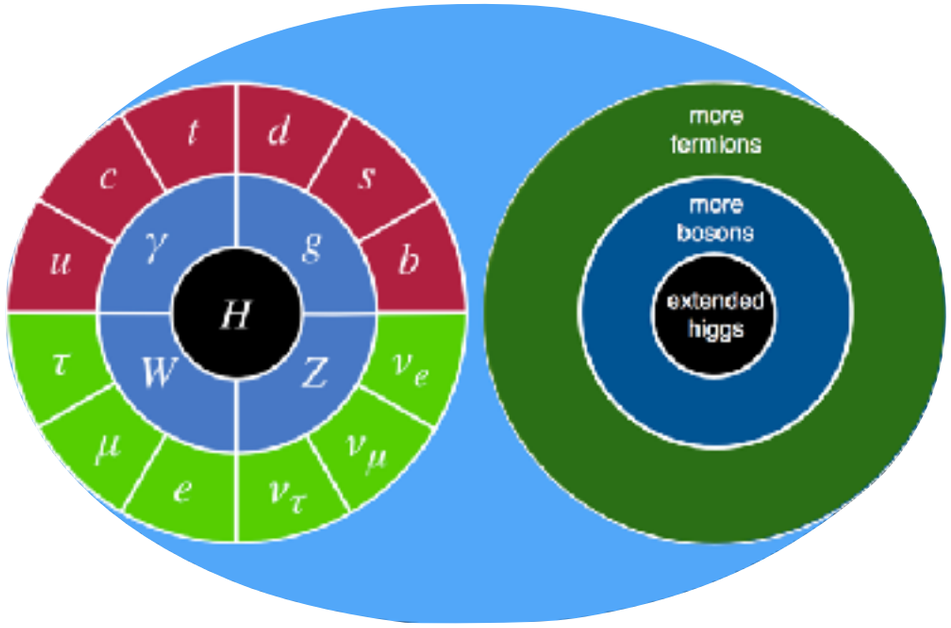
Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30th October 2017 to 1st November 2017

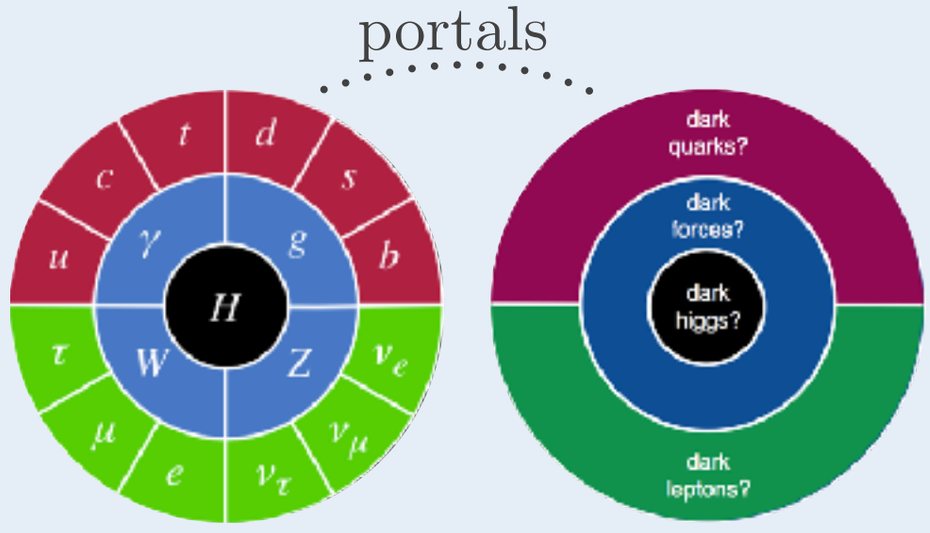
Dark Sector searches

diagrams are a courtesy of M.Williams

1. **Unified theory of DM and SM**
   → at TeV scale (e.g. SuperSymmetry)
   - Direct searches (e.g. jet+MET)
   - Indirect searches via quantum effects in SM decays (flavour physics)



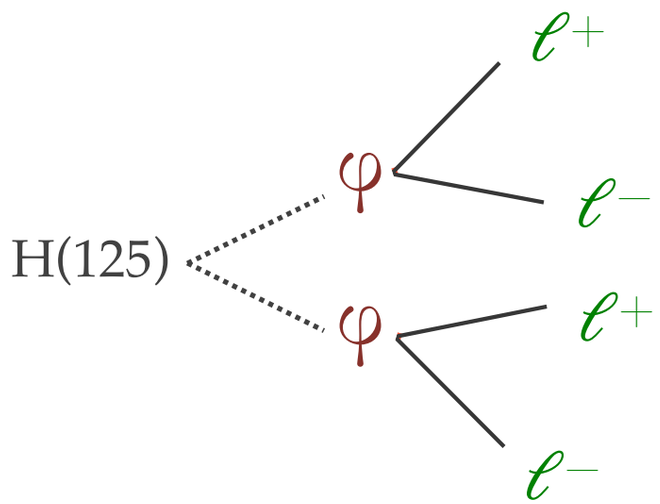
2. **Separated DM sector with portals to SM**
   - Scalar portal (e.g. inflaton)
   - Axion portal (e.g. axion-like)
   - Vector portal (e.g. dark photon)

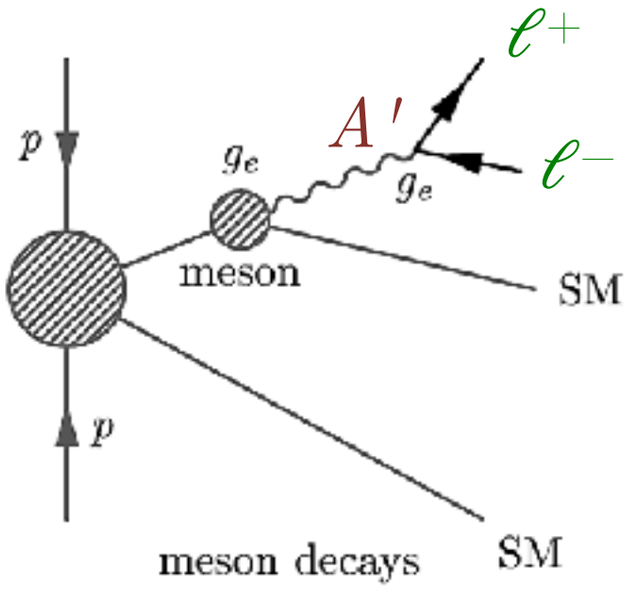


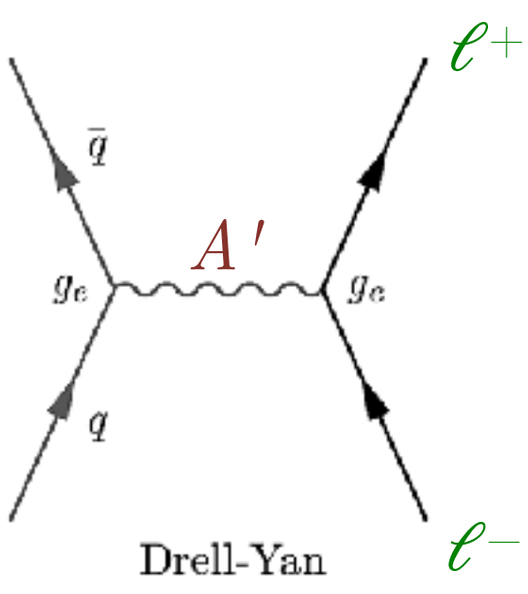
→ see talk by David Curtin

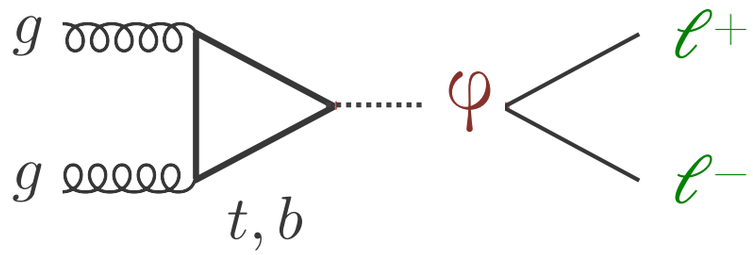
Light dilepton states

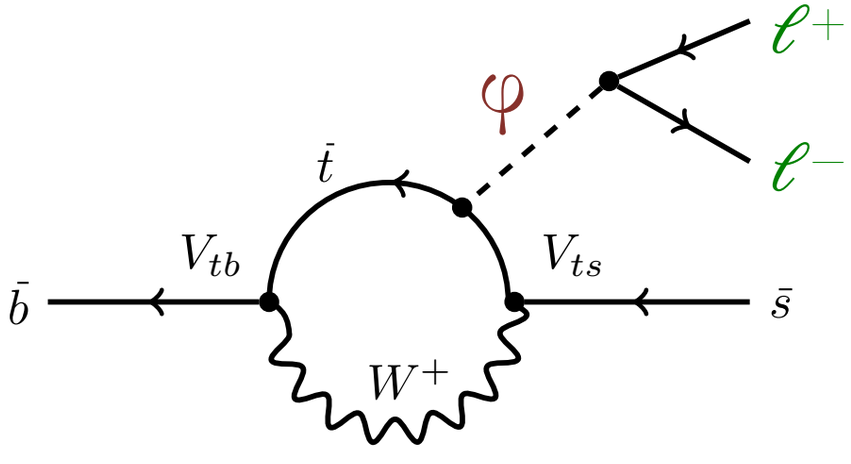
- Very small couplings are allowed
  ⇒ **dilepton** light states often not excluded
- Produced at the LHC via various channels
- Some examples for vectors A' and (pseudo-)scalars φ :









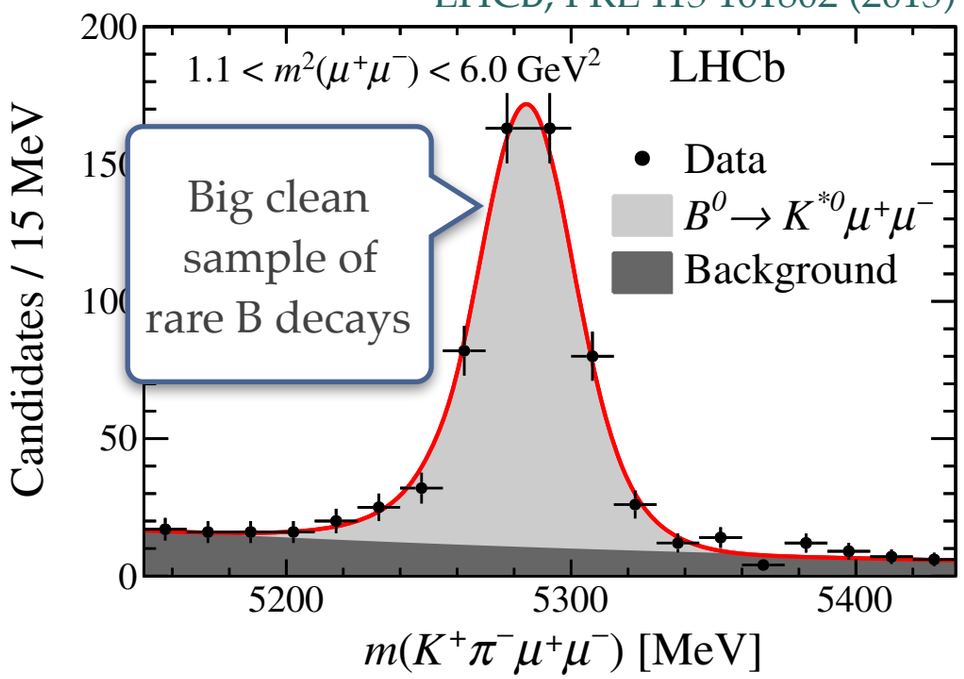


Light dileptons at LHCb

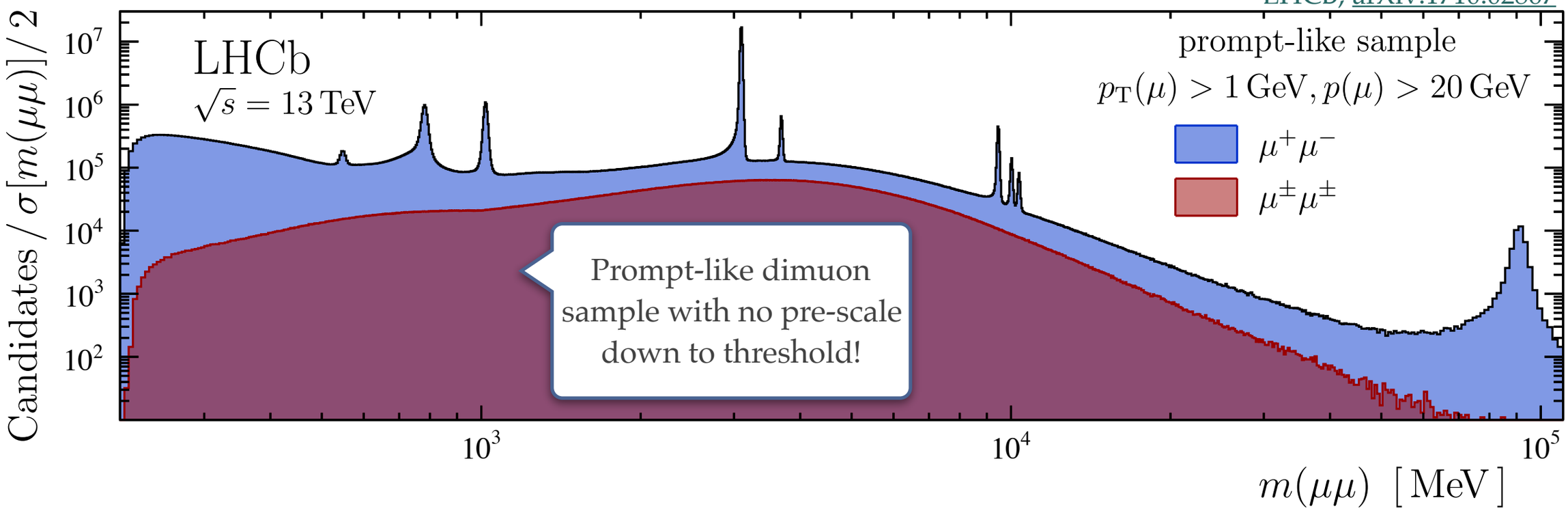
- **LHCb**: very soft triggers, forward acceptance and good mass resolution
- Excellent for light dimuons (both detached and prompt)

→ *see talk by Carlos Vazquez Sierra*

LHCB, PRL 115 161802 (2015)



LHCB, arXiv:1710.02867



Soft triggers at LHCb

- **Trigger upgrade for Phase I (Run 3 2021)**
  - Read-out detector in *real time*
  - Possibility to trigger on much softer object at first level

LHCb Phase I TDR: [LHCB-TDR-016]

- Trigger scheme will be standard for Phase-II upgrade(Run 5)

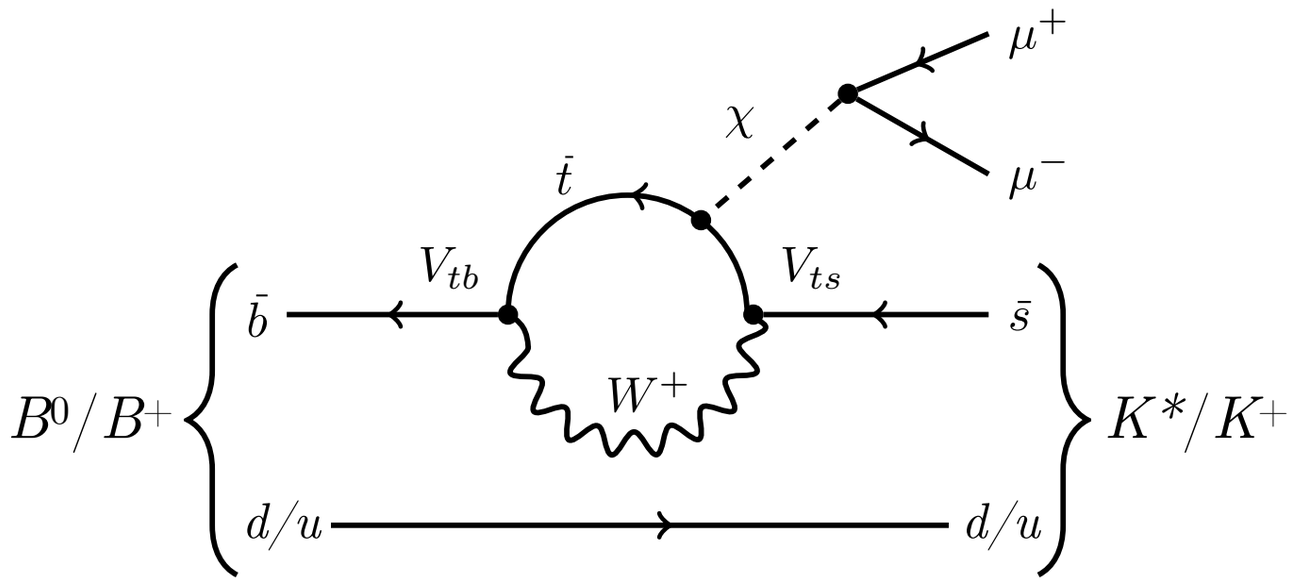
LHCB Phase II EOI: [CERN-LHCC-2017-003]

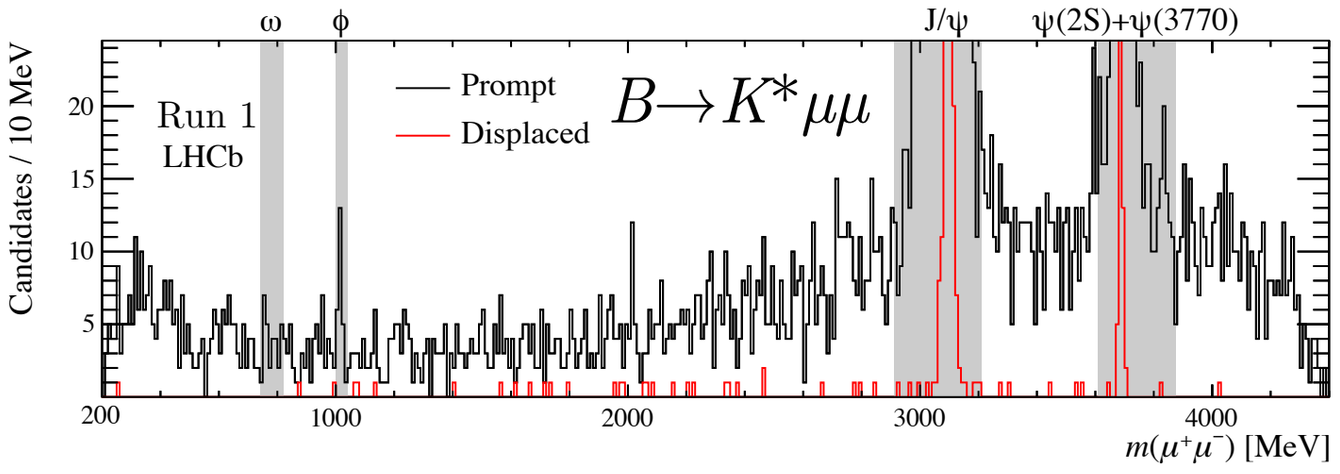
2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
		Run III						Run IV					Run V	
LS2						**LS3**					**LS4**			
LHCb 40 MHz UPGRADE Phase I		$L = 2 \times 10^{33}$			**LHCb Consolidation**			$L = 2 \times 10^{33}$ $50\ fb^{-1}$			**LHCb Ph II UPGRADE ***		$L = 2 \times 10^{34}$ $300\ fb^{-1}$	
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$			**ATLAS Phase II UPGRADE**			**HL-LHC** $L = 5 \times 10^{34}$			**ATLAS**		**HL-LHC** $L = 5 \times 10^{34}$	
CMS Phase I Upgr		$300\ fb^{-1}$			**CMS Phase II UPGRADE**						**CMS**		$3000\ fb^{-1}$	
Belle II		$5\ ab^{-1}$	$L = 8 \times 10^{35}$		$50\ ab^{-1}$									

Dark Sector in $B \to K^{(*)} \chi(\mu\mu)$

LHCb, PRL 115 161802 (2015)
LHCb, PRD 95, 071101(R) (2017)

- Look for new dark-sector bosons in $b \to s$ penguin transitions
  - Can radiate a **(pseudo-)scalar** from the top loop
- LHCb collected world record samples of rare decay $B \to K^{(*)}\mu\mu$
- Allow detached $\mu\mu$ (within VELO)
  - small SM mixing can give lifetime
- Search for narrow peak in m($\mu\mu$)
  - B mass constrained
    - m($\mu\mu$) resolution 3-9 MeV



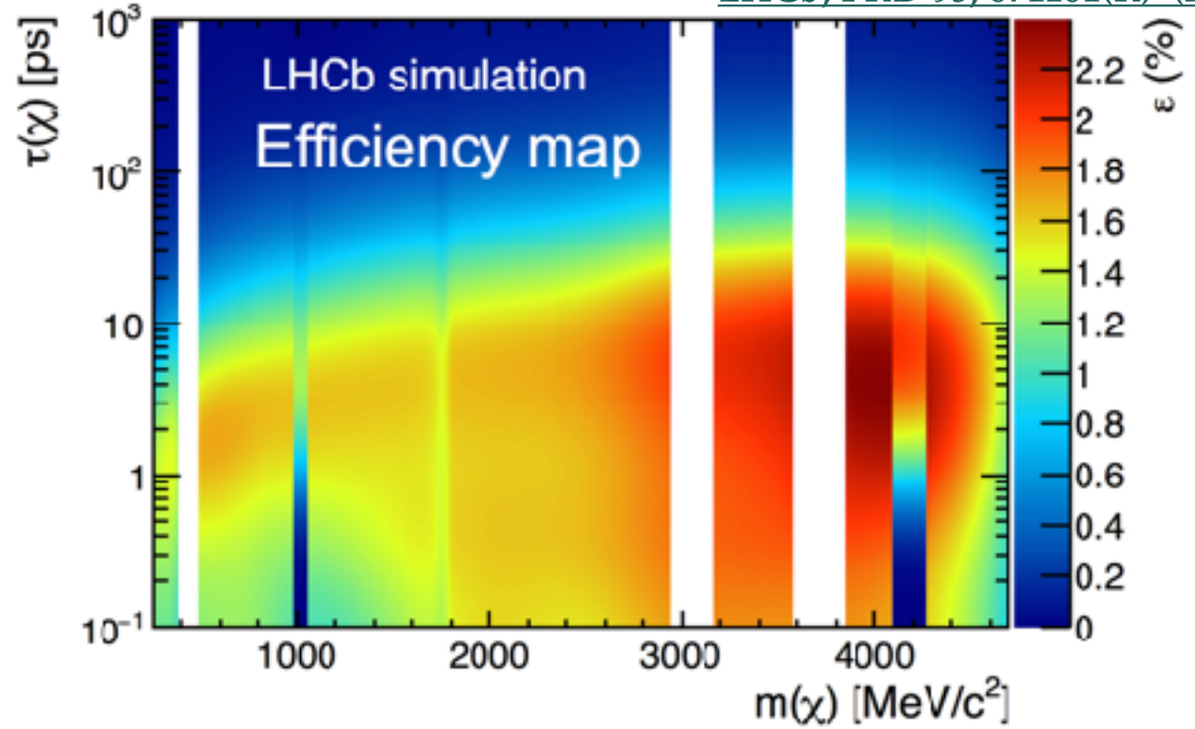


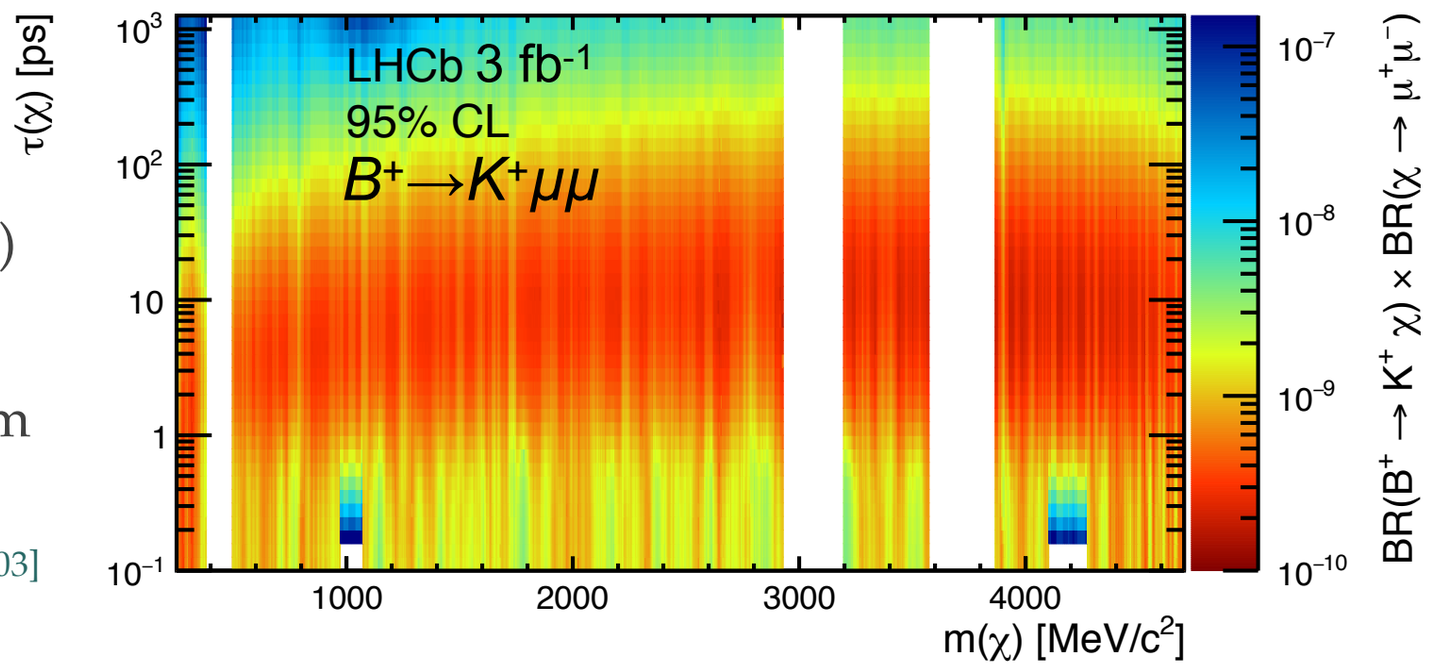
Dark Sector in $B \to K^{(*)} \chi(\mu\mu)$

LHCb, PRL 115 161802 (2015)
LHCb, PRD 95, 071101(R) (2017)

- Decays inside the VELO
  - efficiency drops at ~100 ps
- **Model-independent limit on mass versus lifetime**
- Reach is only limited by statistics
  - prompt has irreducible SM bkg
  - displaced is almost bkg free
- **Possible improvements**:
  - Use inclusive $B \to X_s \mu\mu$ (10× larger BR)
  - Vertices downstream of the VELO
    - Specialised processors for downstream track finding for Phase II upgrade?

LHCB Phase II EOI: [CERN-LHCC-2017-003]

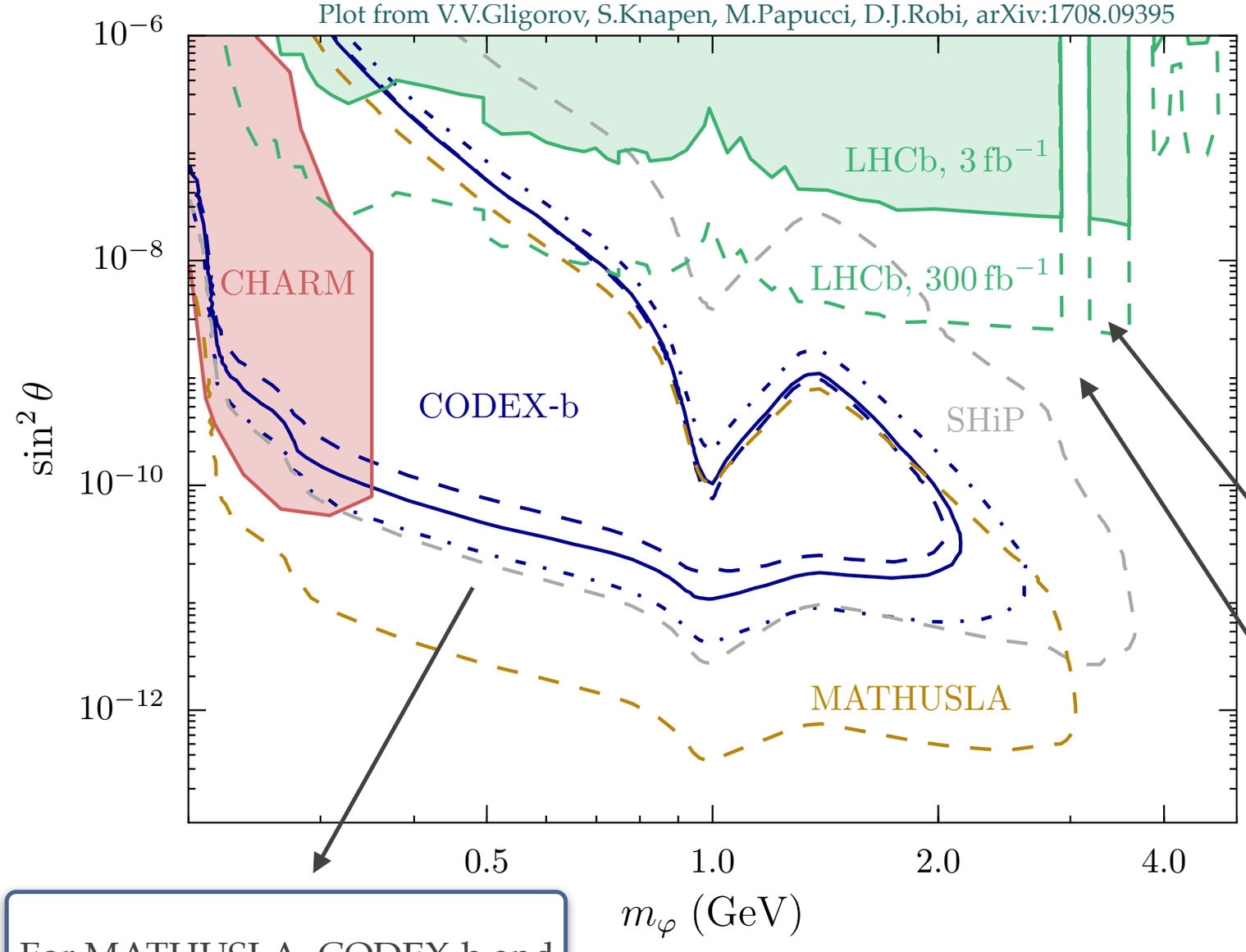




Dark Sector in $B \to K^{(*)} \chi(\mu\mu)$

Phys Rev Lett 115 161802 (2015)
Phys Rev D 95, 071101(R) (2017)

Plot from V.V.Gligorov, S.Knapen, M.Papucci, D.J.Robi, arXiv:1708.09395



For MATHUSLA, CODEX-b and FASER see D.Curtin's talk

- **Constraint on light scalars mixing with the SM Higgs**

$\tau \propto 1/\theta^2 \qquad \mathcal{B}(B^+ \to K^+ \chi) \propto \theta^2$

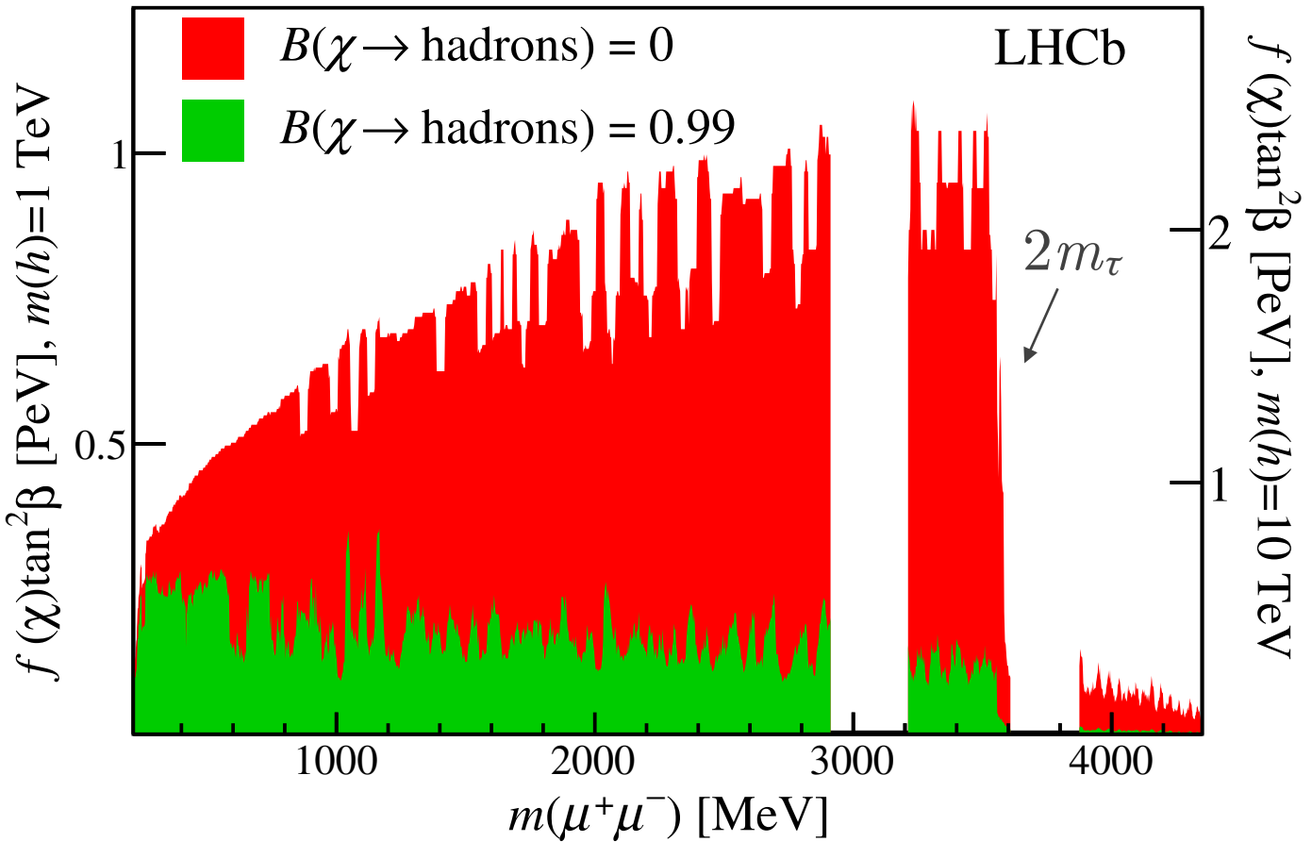
B.Batell, M.Pospelov, A.Ritz, PRD 83, 054005 (2011)
F.Bezrukov, D.Gorbunov, JHEP05(2010)010, JHEP07(2013)140

- **New parameter space is unexplored by current and future experiments**
  - 300 fb^{-1} expected reach (no downstream dimuons)
  - Could significantly extend reach with downstream trigger

Hidden Sector in $B \to K^{(*)} \chi(\mu\mu)$

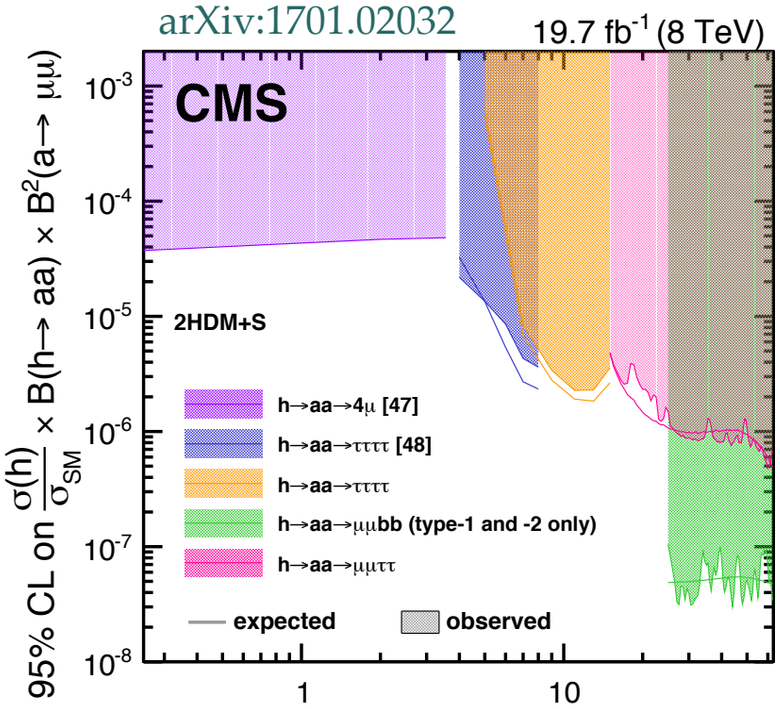
Phys Rev Lett 115 161802 (2015)

- Constraint on **axion portal** model
  M.Dine, W.Fischler, M.Srednicki PL 104B 199-202 (1981)
  A.R.Zhitnitsky Sov.J.Nucl.Phys. 31, 260 (1980)
  - 3 fb^{-1} already reaching PeV for the Peccei-Quinn symmetry breaking scale (f_a)
  - Very roughly BR $\sim 1/f_a^2$ and $\tau \sim f_a^2$
  - Future searches can in principle access the range of f_a that could give rise to an observable signal in LIGO/VIRGO (10-100 PeV)
    P. S.Bhupal Dev, A.Mazumdar PRD93 no.10, 104001 (2016)



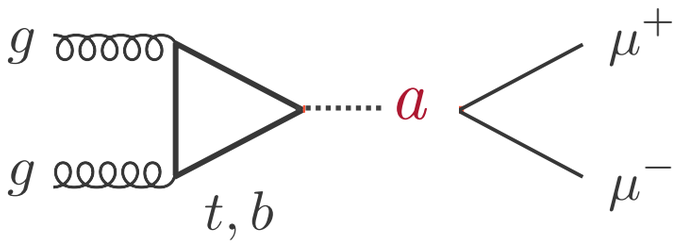
Light pseudo-scalar searches

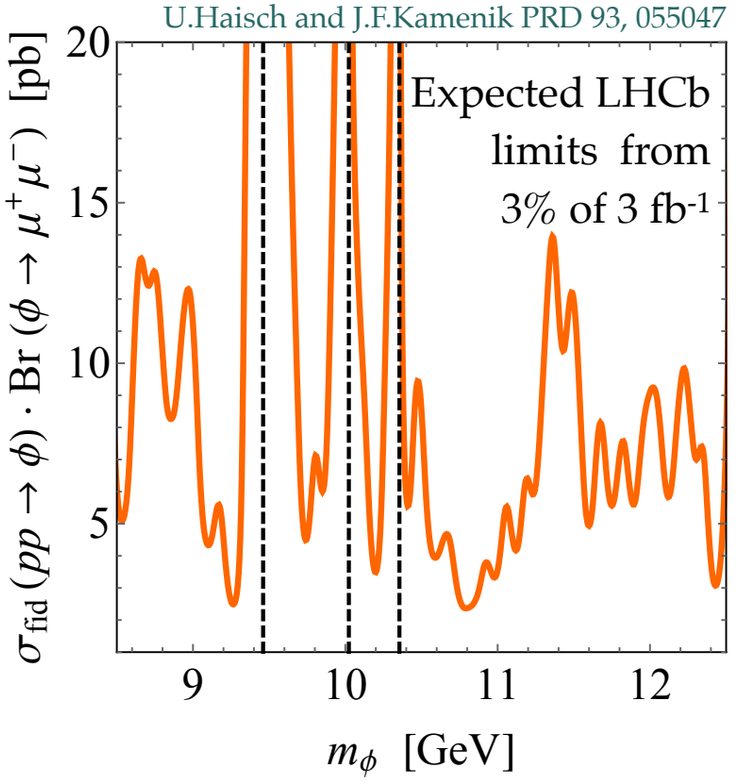
- Arise in various complete theories (e.g. NMSSM)
- Can mix with the SM Higgs ⇒ search in Higgs decays (ATLAS/CMS)



- Can also search for light scalars directly produced in gg fusion using LHCb soft triggers

U.Haisch and J.F.Kamenik PRD 93, 055047

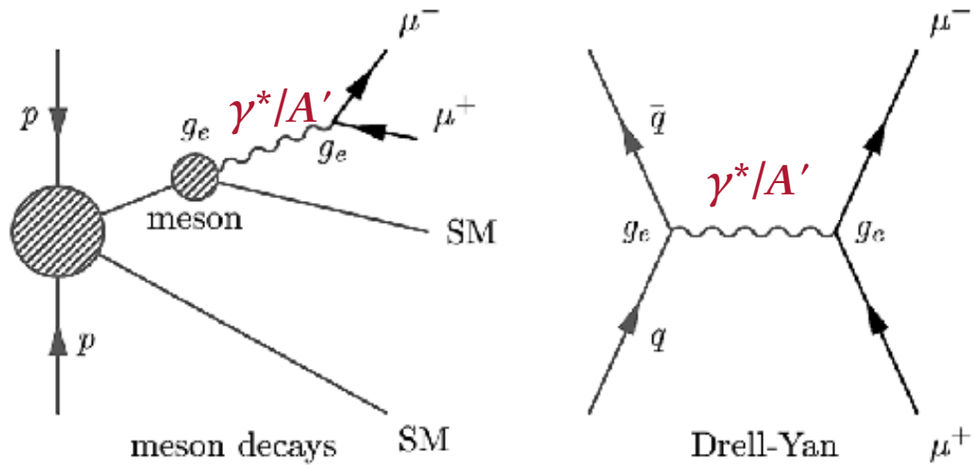




Dark Photons

LHCB, arXiv:1710.02867

- Dark photons arise naturally in several dark sector models
- Kinetic mixing loop involving mass up to Planck scale
  ⇒ mixing parameter ε^2 can be as small as 10^{-14}
- Dark photon masses can be low
- Large parameter space → worldwide effort
- Can search at the LHC!

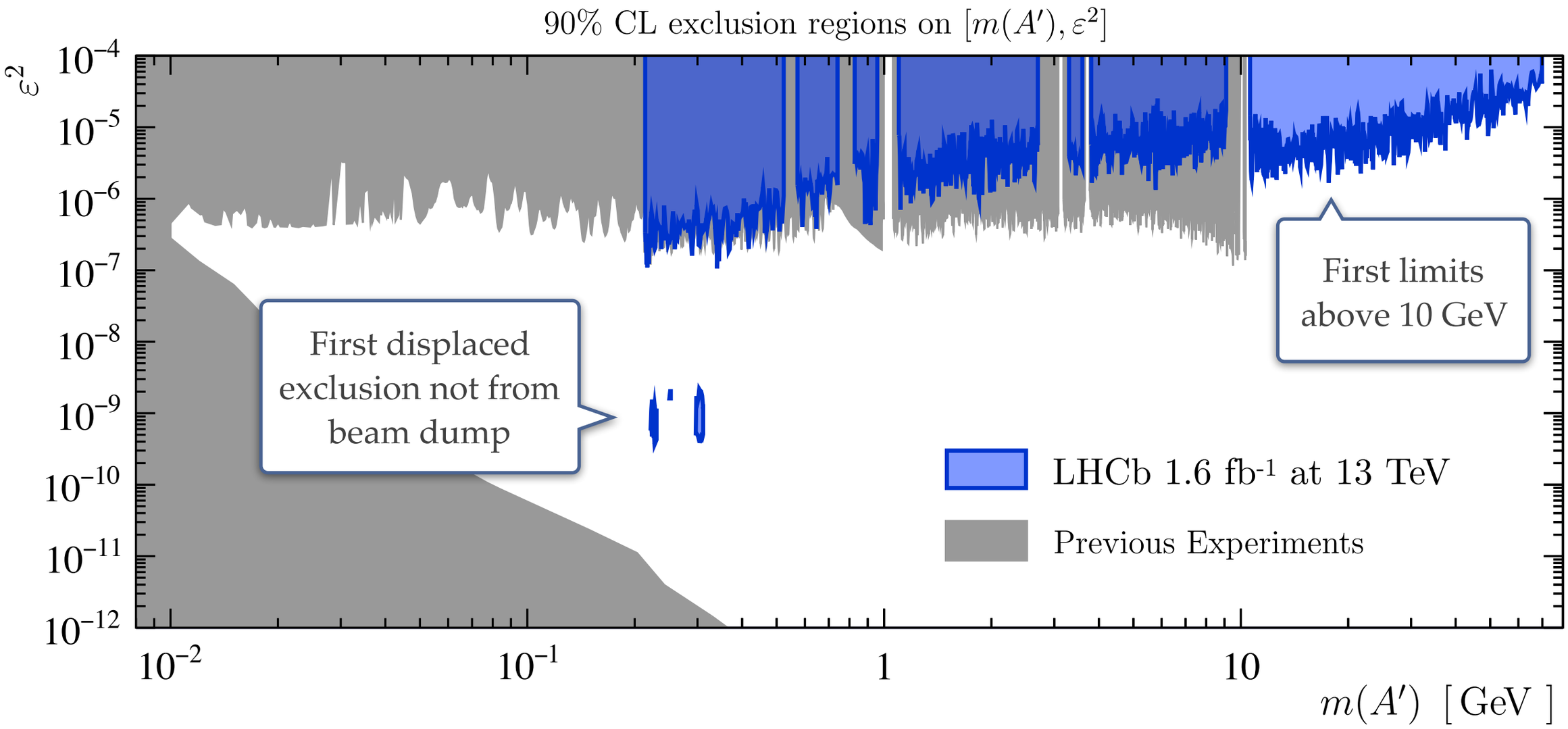


- Dark photon A' inherits production mechanisms from SM photon
- Use **data-driven normalisation** to off-shell photon γ^*

Dark Photons

LHCB, arXiv:1710.02867

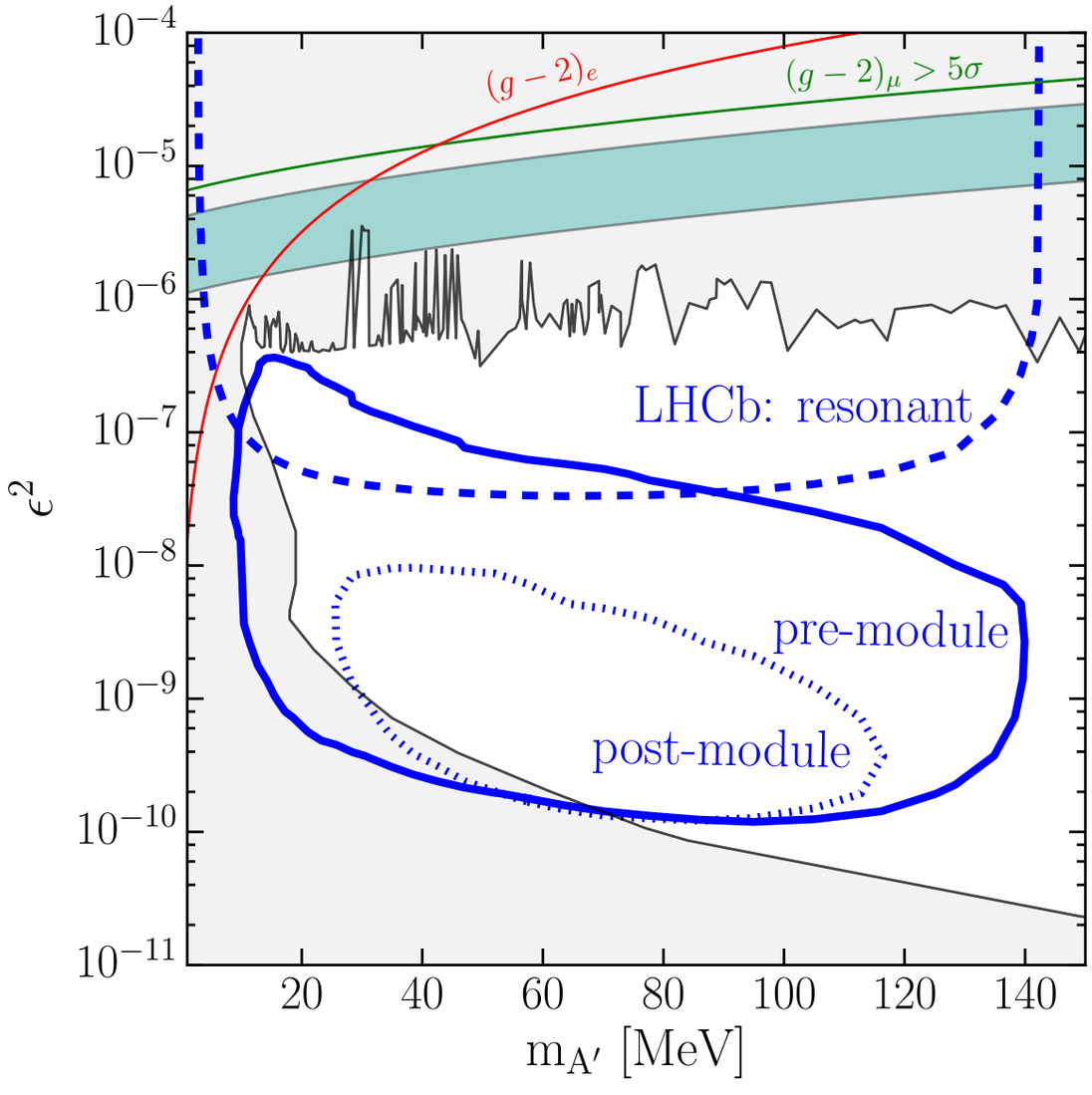
- **First results** already obtained with 1.6 fb^{-1} at 13 TeV
  - **Prompt search** in large range $2\,m_\mu < m(\mu\mu) < m(Z)$
  - **Displaced search** in sensitive region $214 < m(A') < 350$ MeV



Dark Photons from charm

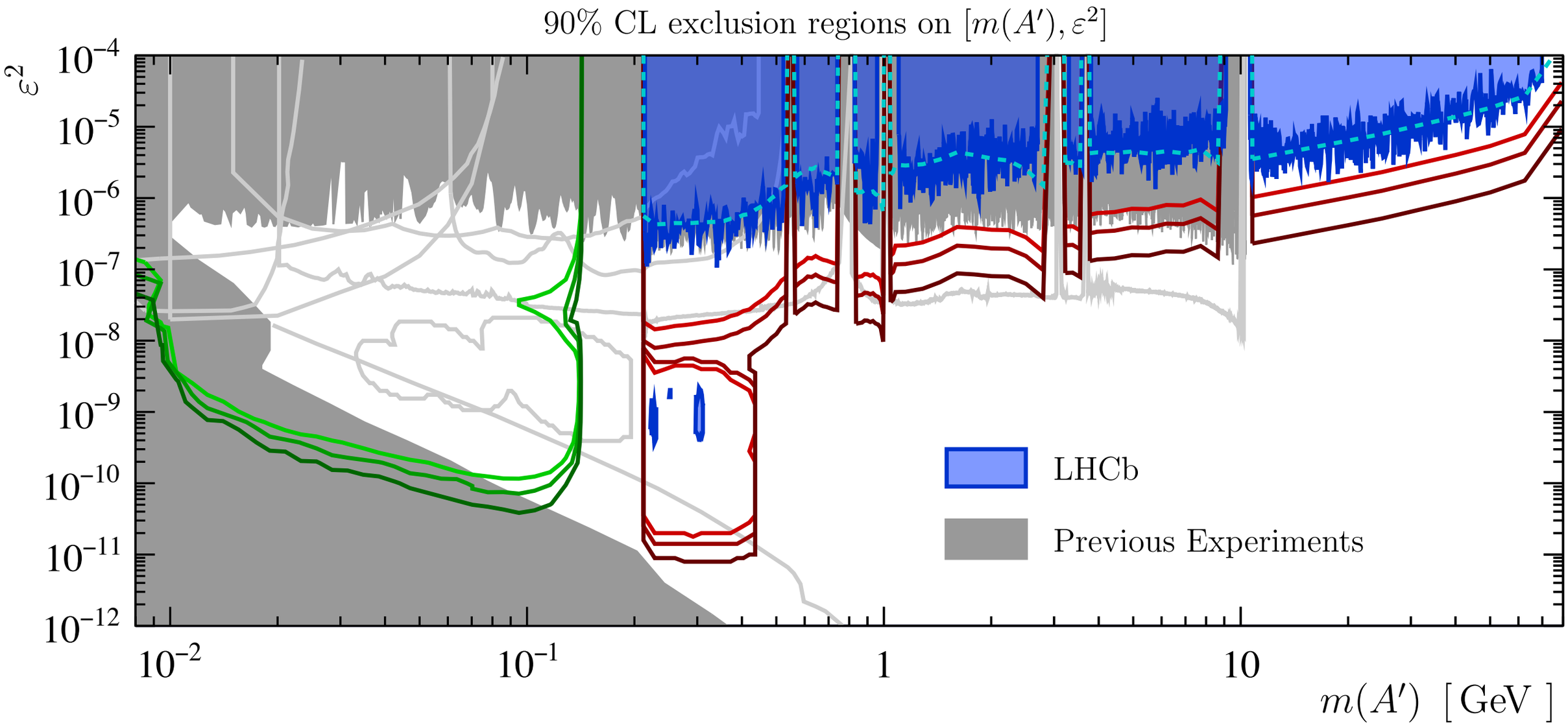
Ilten, Thaler, Williams, Xue PRD 92 no.11, 115017 (2015)

- Can cover region below $2m_\mu$ using charm decays $D^{*0} \to D^0 A'(ee)$
  - Requires upgraded trigger to select efficiently soft final state
  - Get **300×10⁹** $D^{*0} \to D^0\gamma$ **per fb⁻¹**
  - Both displaced and prompt searches



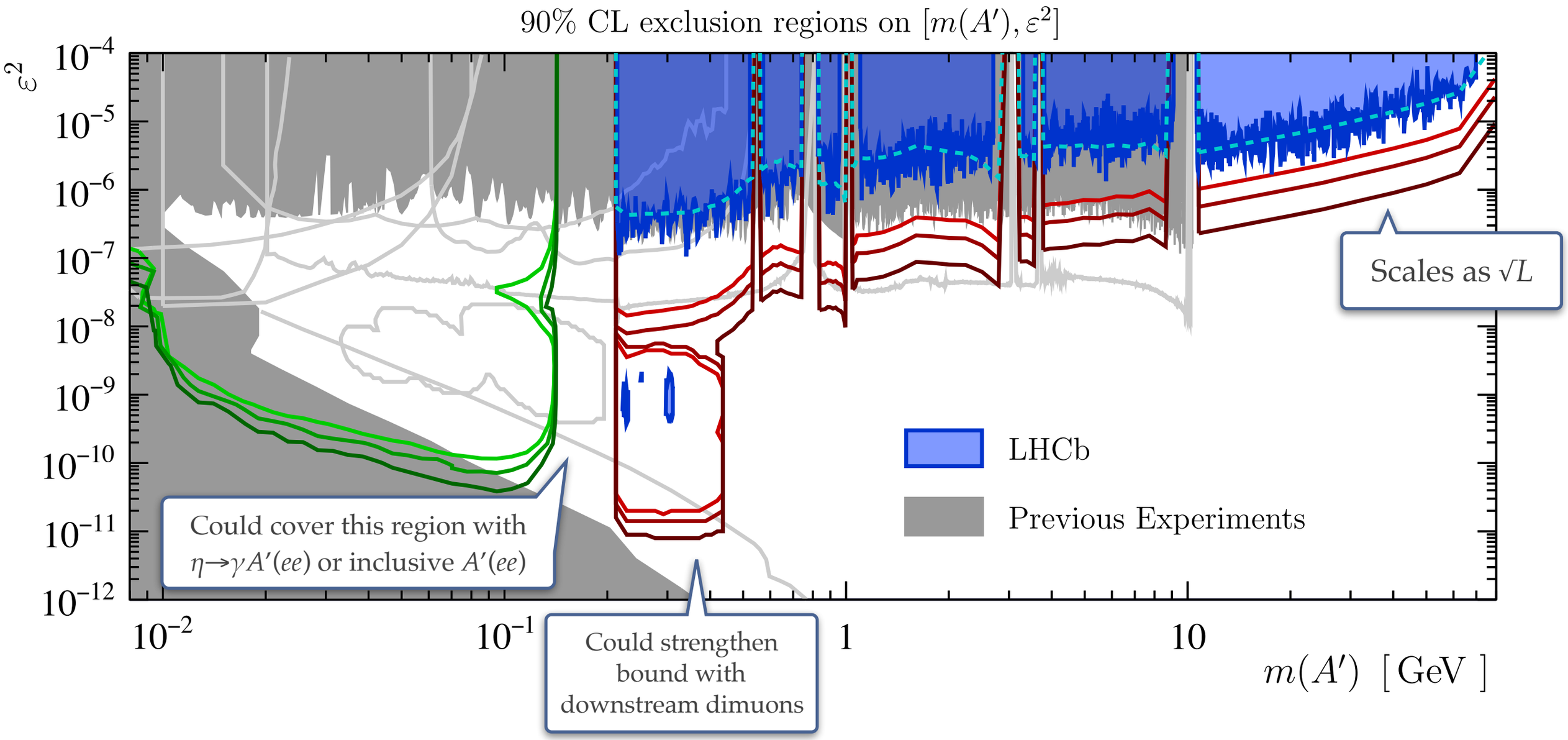
Dark Photons reach

Ilten, Soreq, Thaler, Williams, Xue, PRL. 116 (2016) no.25, 251803



Dark Photons reach

Ilten, Soreq, Thaler, Williams, Xue, PRL. 116 (2016) no.25, 251803



Conclusions

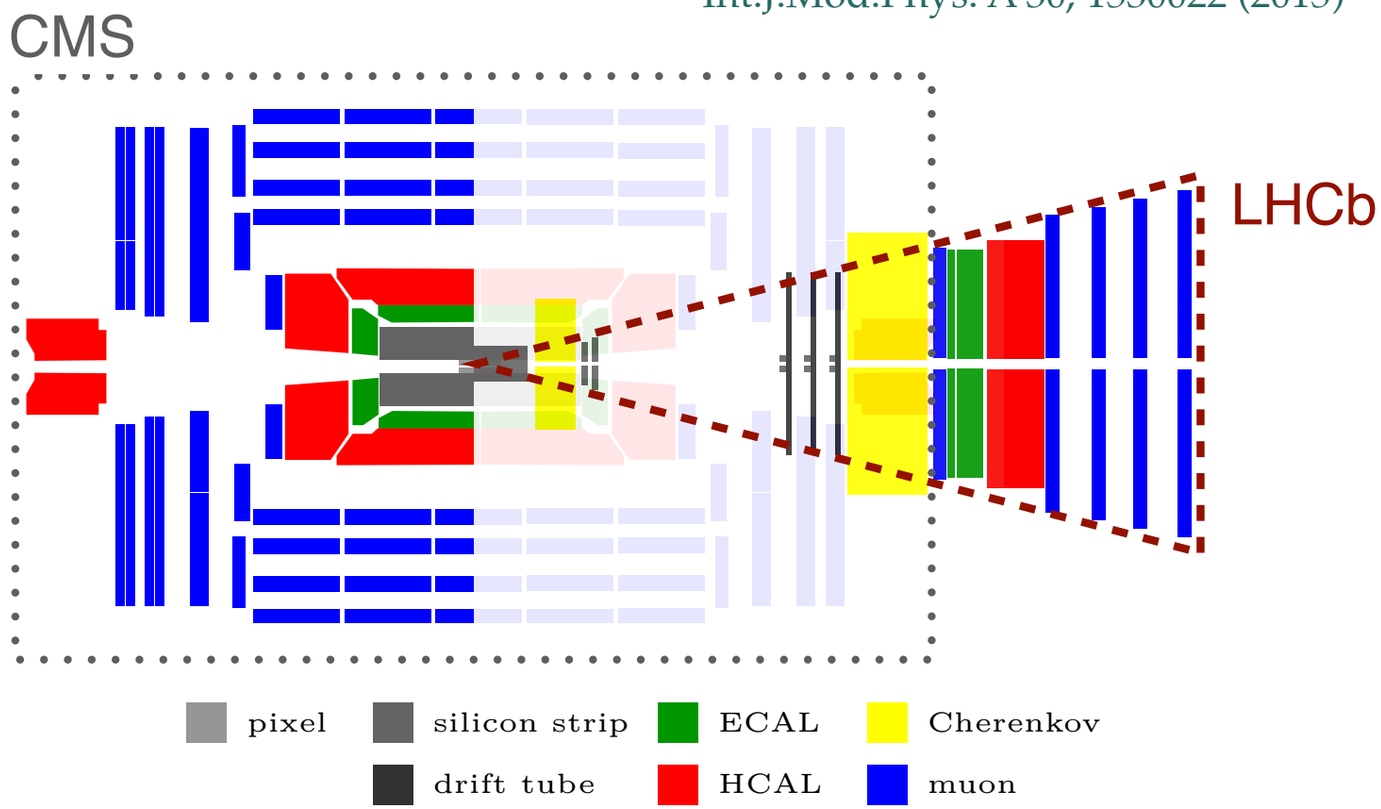
- Several dark-sector models give light (displaced) dilepton resonances
- LHCb has unique capabilities and the upgraded trigger should greatly expand its low-mass BSM potential
- High luminosity would extend the reach of current searches at much lower coupling (even with present performances)
  - Also keep in mind 95% exclusion is not 5σ discovery
- Flexible LHCb trigger allows to expand to plenty other ideas such as: right-handed neutrinos $N_{2,3} \to \mu^+\pi^-$, LFV resonances $A \to e^+\mu^-$,…more?
- Low couplings, low masses: **high luminosity can shed light on dark sectors**!

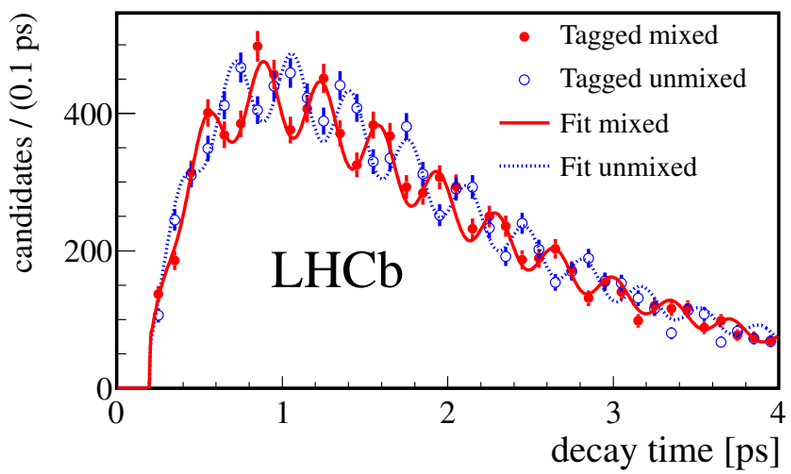
BACKUP

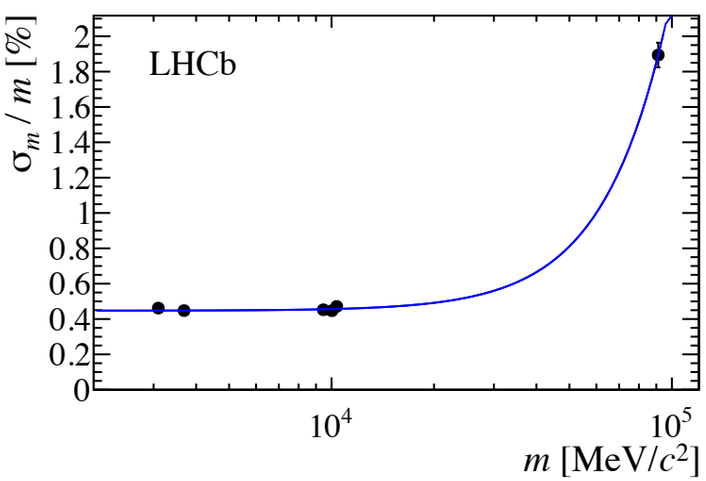
The LHCb detector

Int.J.Mod.Phys. A 30, 1530022 (2015)

- At LHC pp collisions (7-13 TeV)
- Fully instrumented in **forward** region $2<\eta<5$ for B physics
  - also **light states** in general
- Excellent vertex resolution
  - B_s oscillation at 40 fs (average boost $\beta\gamma \sim 3$)
- Excellent mass resolution
  - ~0.5% on $m(\mu\mu)$ up to 20 GeV
- Unique PID capabilities
  - dedicated Cherenkov detectors
- Good jet reconstruction
  - 10-20% energy resolution for jets with $p_T > 10$ GeV
  - $b(c)$ tagging eff 65%(25%) for 0.3% contamination

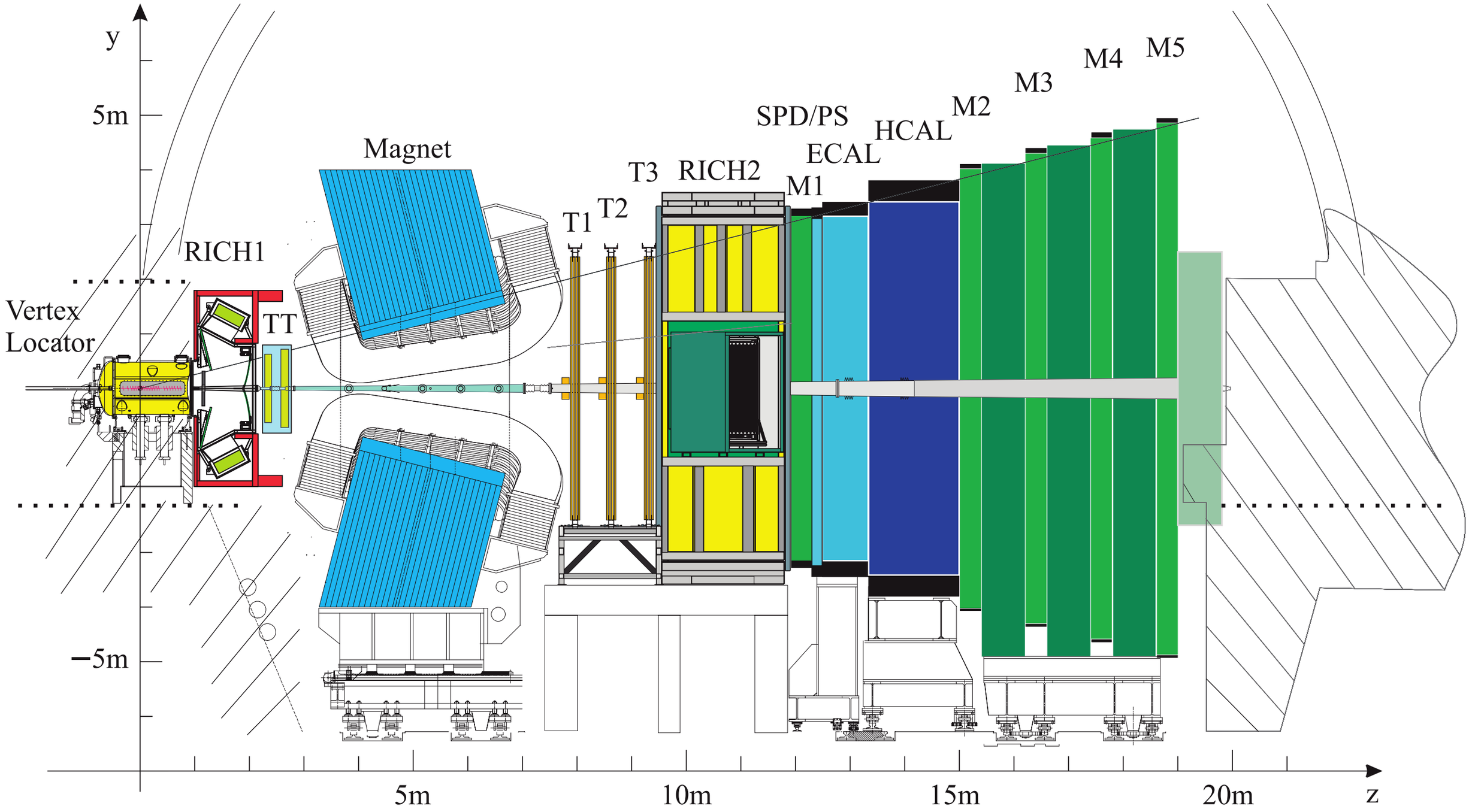






The LHCb detector

Int.J.Mod.Phys. A 30, 1530022 (2015)

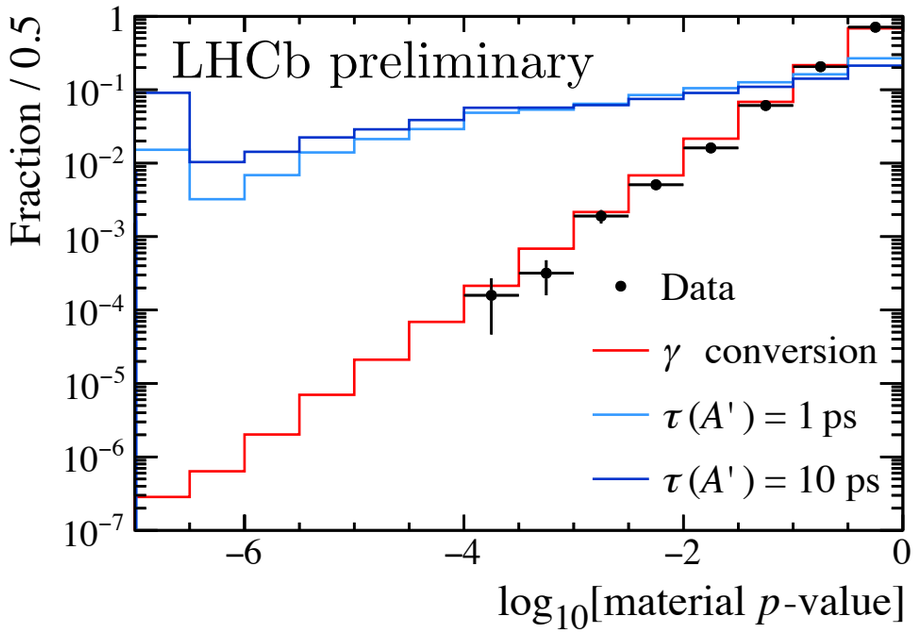


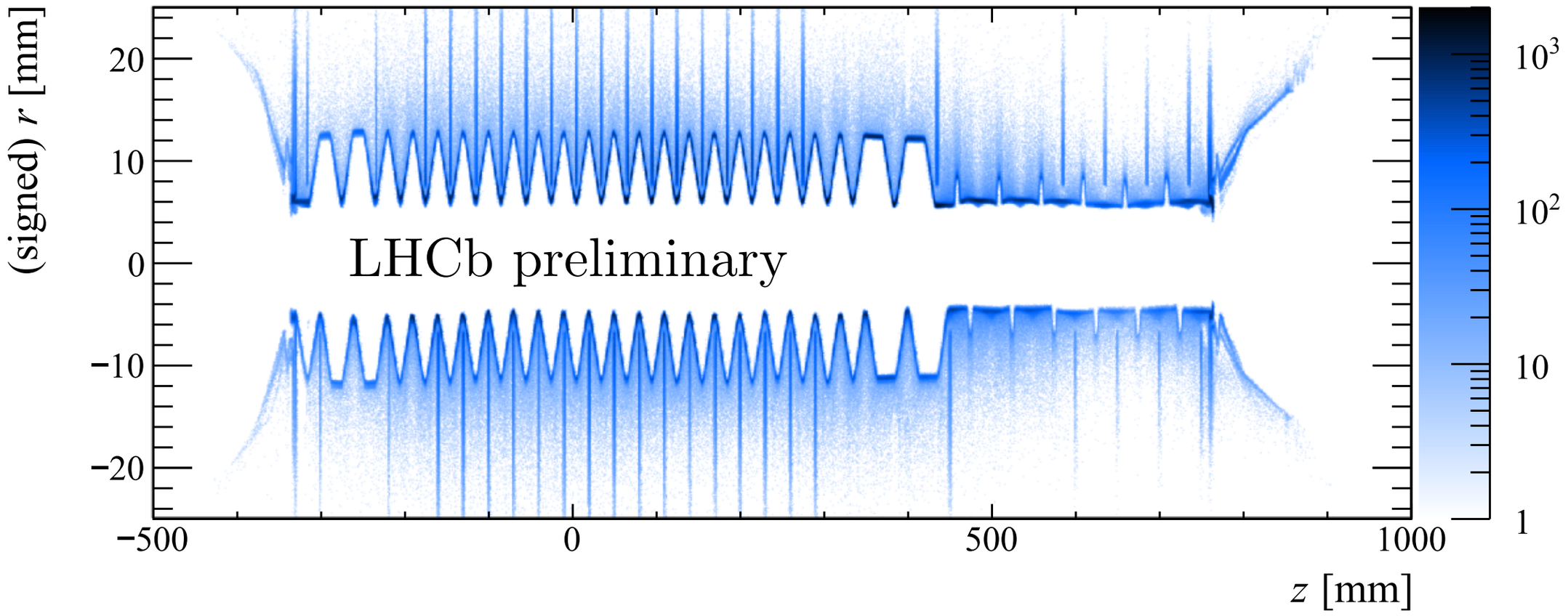
Dark Photons

Detector Performance paper in preparation

- For displaced searches:
  - Need to reduce background from photon conversions
  - New **material map** based on material interactions from beam-gas collisions
- Removal of RF foil in Phase II upgrade?

LHCB Phase II EOI: [CERN-LHCC-2017-003]





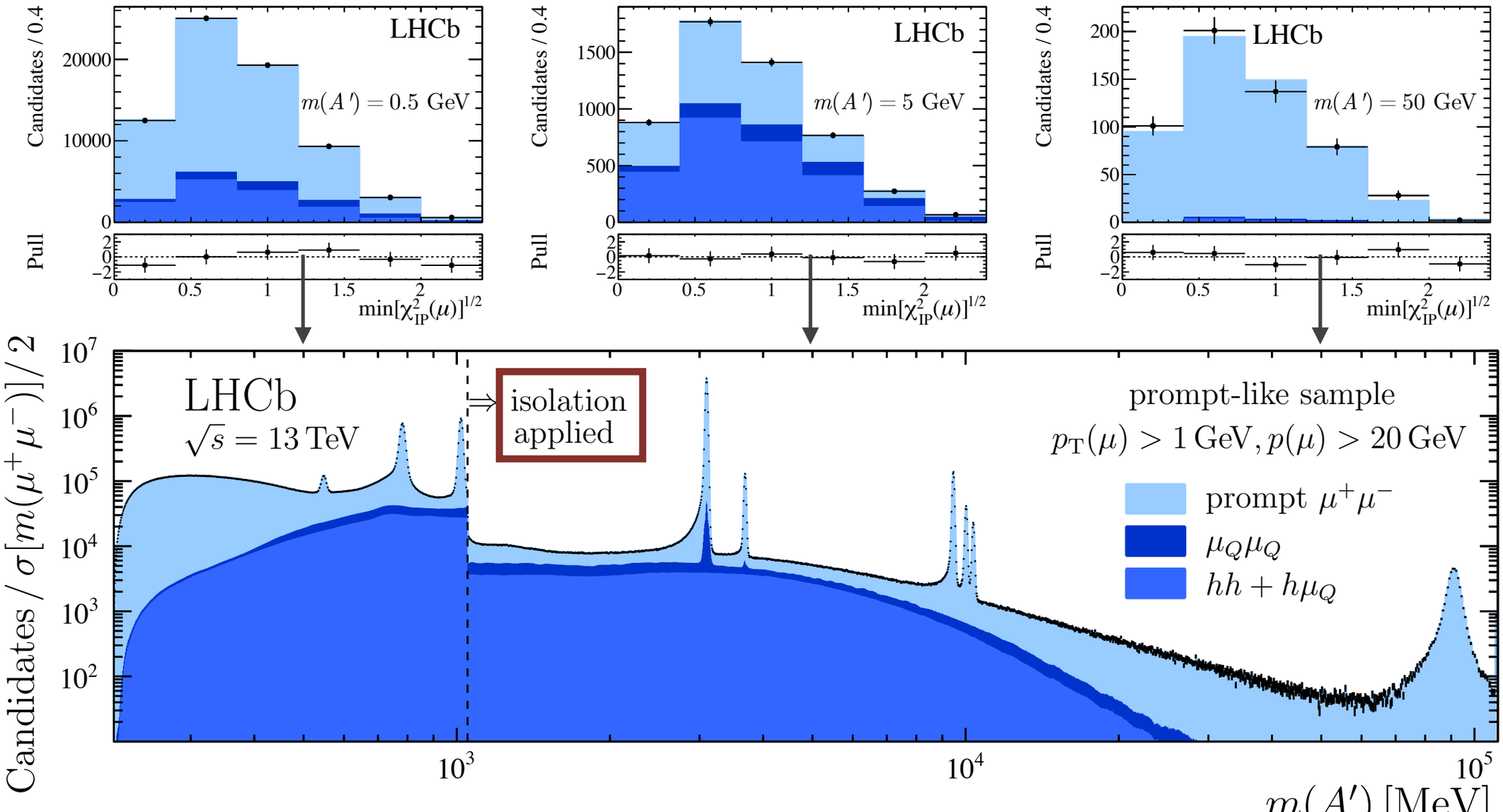
Dark Photons

LHCb-PAPER-2017-038 (soon in arXiv)

Using templates for $\min[\chi^2_{\text{IP}}]$ (small mass dep)

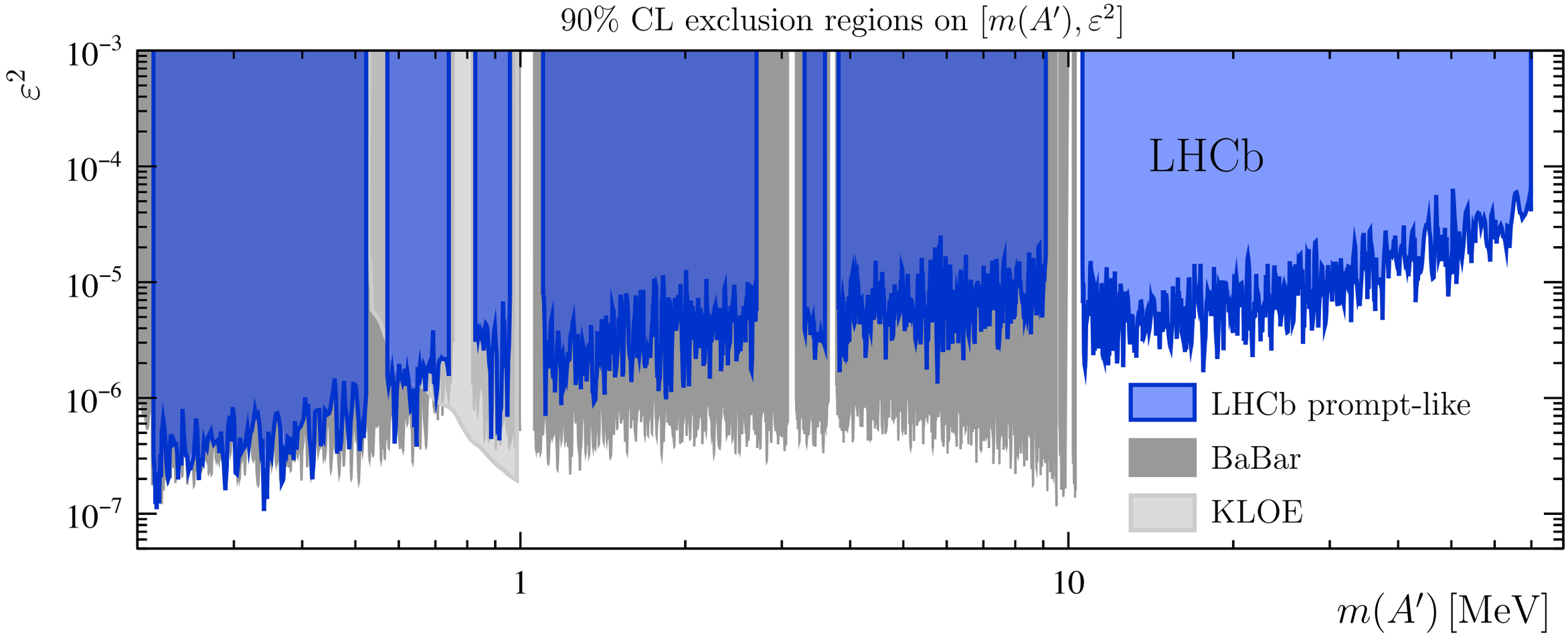
- prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ → from simulation (validated)
- $hh + h\mu_Q$ → from same-sign dimuons (corrected)

(μ_Q is a muon from a heavy-flavour decay)



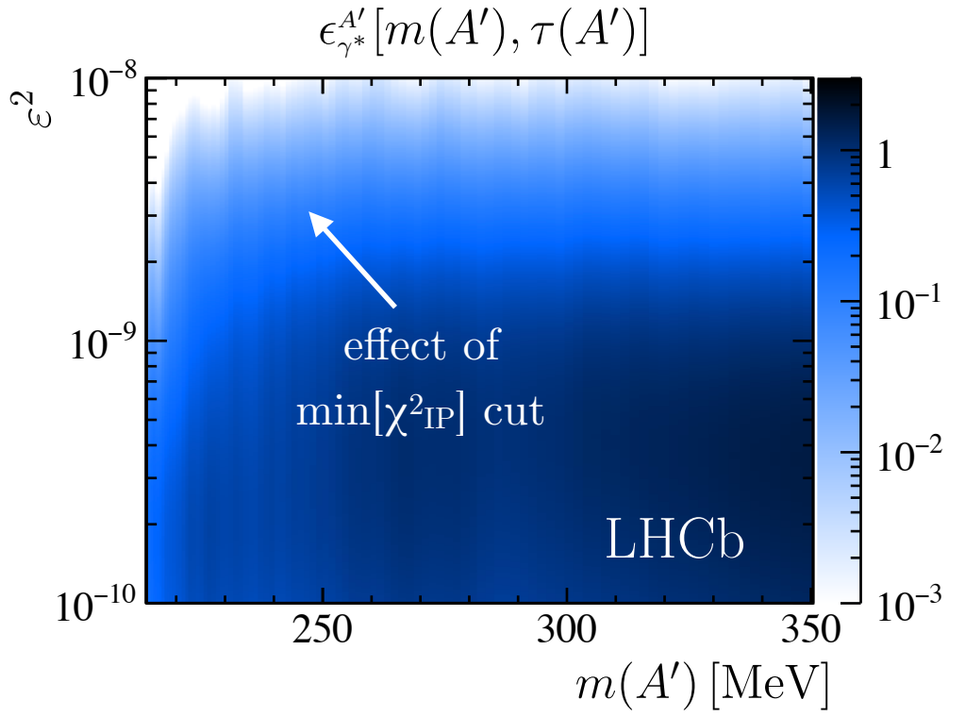
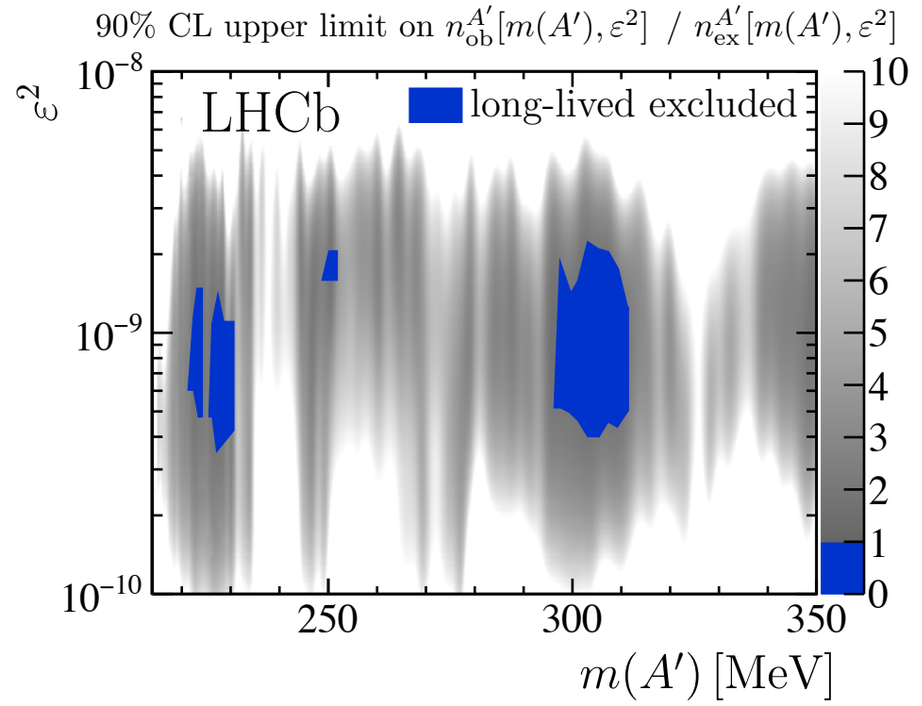
Dark Photons

LHCb-PAPER-2017-038 (soon in arXiv)



- No significant excess found
- First limit on dark photons for $m(A') > 10\,\text{GeV}$
- Already competitive for $m(A') < 0.5\,\text{GeV}$

Dark Photons

LHCb-PAPER-2017-038 (soon in arXiv)

- **Displaced search** in region $214 < m(A') < 350$ MeV
- Even looser online requirements on $p_T(\mu)$
- Other backgrounds:
  - Muons from b-hadron decays
    → isolation decision tree (from $B_s \to \mu\mu$)
  - Mis-id pions from $K_S \to \pi\pi$ tail
    → modelled from PID sideband
- Fit in bins of mass and lifetime
  - Also using consistency of decay topology χ^2
  - Extracting p-values and confidence intervals
- **No significant excess is found**
  - Already excluding a small region of (ε^2, m)
  - First limit ever not from beam-dump!